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SOURCE CONTROL OF TURBOMACHINE DISCRETE-FREQUENCY TONE GENERATION

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ABSTRACT

Turbomachine discrete-frequency tones, a significant environmental concern, are generated by rotor-stator interactions. Specific spatial modes are generated in the duct by rotor-stator interactions. However, only certain of these modes propagate to the far-field, with these representing the far-field discrete-frequency noise. This paper describes a series of fundamental passive and active discrete-frequency noise source control experiments. Passive source control is accomplished by rotor detuning, i.e., nonuniform rotor blade circumferential spacing. As the detuned rotor excites the stator at many more multiples of rotor shaft frequency than a uniformly spaced rotor, rotor detuning is evaluated using the overall intensity level which includes the influence of tones over the entire spectrum. Data are acquired and analyzed which demonstrate that rotor detuning consistently reduces the overall intensity level of the rotor-stator interaction when the spatial mode of interest is cut-on. With the active source control, the acoustic propagating modes are canceled by generating control propagating waves which interact with those generated by the rotor-stator interaction. This is accomplished utilizing a speaker-dipole arrangement around each stator, with reductions of the primary interaction mode achieved.

INTRODUCTION

Aeroacoustics is an increasingly important issue in the design of advanced gas turbine engines. Engine certification requires meeting prevailing noise regulations, such as the U.S. FAR 36 Stage 3 rules to be implemented through the end of this decade. In addition, more stringent noise level guarantees are often required of the engine manufacturer by airlines to meet tougher local airport noise requirements. Also, there is a near certainty that more stringent Stage 4 requirements will require an additional reduction of 5-10 EPNLdB.

As engines with higher bypass ratios have been introduced, turbomachinery noise, i.e., fan, compressor, and turbine generated noise, has become more important, with jet exhaust mixing noise contributing less to the total engine noise signature. Figure 1 depicts the primary noise sources for a modern high bypass ratio engine: the fan, the low-pressure or booster compressor, and the low pressure turbine. Their noise signatures, include a broadband noise level, with large spikes or tones at multiples of the blade passing frequency. For subsonic fans, the acoustic spectrum discrete-frequency tones are usually 10-15 dB above the broadband level.

Discrete-frequency tones are generated by periodic blade row unsteady aerodynamic interactions between adjacent blade rows. Namely, turbomachine blade rows are subject to spatially nonuniform inlet flow fields resulting from either potential or viscous wake interactions. Potential flow interactions result from variations in the pressure field associated with the blades of a given row and their effect on the blades of a neighboring row moving at a different rotational speed. This type of interaction is of concern when the axial spacing between neighboring blade rows are small or flow Mach numbers are high. Wake interactions result from the impingement of wakes shed by one or more upstream rows upon the flow through a downstream blade row. This type of interaction can persist over considerable axial distances. Both of these interactions result in the generation of acoustic waves which may propagate unattenuated and also interact with other blade rows.

This paper is directed at the fundamentals of both passive and active source control of these discrete-frequency tones. A series of passive and active discrete-frequency noise source control experiments are performed in the Purdue Rotating Annular Cascade Research Facility. The passive source control technique considered is rotor detuning, defined as nonuniform rotor blade circumferential spacing. Rotor detuning decreases the fundamental tone by breaking the
fundamental periodicity of blade passing. In the active source control technique, the acoustic propagating modes, i.e., the far
field tone noise, are canceled by generating control propagating waves which interact with those generated by the rotor-stator
interaction.

With rotor detuning, the modulated blade spacing breaks up the fundamental periodicity of the rotor-stator
interaction by affecting the frequency content of the excitation. This in turn affects the frequency content of the acoustic
response. Thus, a stator excited by a uniformly spaced tuned rotor responds at only multiples of the rotor blade pass
frequency, but a stator excited by a detuned rotor responds at many more multiples of the rotor shaft pass frequency.

The active source control is based on the fact that the far field discrete tones are the acoustic propagating modes
generated by the rotor-stator interaction. Thus, far-field tonal noise source control can be accomplished by generating
control propagating waves which interact with and cancel those generated by the rotor-stator interaction. The origin of the
acoustic response of the rotor-stator interaction is the stator vane unsteady surface pressures, theoretically modeled as dipole
sources. As a result, a speaker-dipole control system naturally generates the spatial modes of the rotor-stator interaction.
Thus, the active discrete-frequency noise source control is accomplished utilizing a speaker-dipole arrangement around each
stator, producing control propagating acoustic waves which naturally mimic the rotor-stator interaction generated spatial
modes, with the control parameter being the phase angle between the rotor wake and the speaker-dipole.

DISCRETE-FREQUENCY NOISE GENERATION

The model to analyze the discrete-frequency noise generated in a turbomachine considers a rotor with $N_{\text{blades}}$
interacting with a stator row with $N_{\text{vanes}}$ vanes in a duct. The acoustic response of a stator excited by a rotor is described
by the wave equation applied to an annular duct with uniform steady axial flow. The acoustic response of the rotor-stator
interaction is characterized by the generation of spatial modes at the multiples of the rotor blade passage. The axial
propagation or decay of the spatial modes can then be determined. The propagating spatial modes represent the sound which
reach an observer in the far-field.

Rotor-Stator Interactions

The flow in an annular duct is described by the three-dimensional wave equation, derived by considering the flow to be
inviscid and compressible with small unsteady perturbations.

$$
\left( \frac{\partial}{\partial t} + U_\infty \frac{\partial}{\partial \xi} \right)^2 p = a_\infty^2 \left( \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial \xi^2} \right) p
$$

where $\xi$, $r$ and $\theta$ are the axial, radial and circumferential coordinates, $p$ is the acoustic pressure, and $U_\infty$ and $a_\infty$ are the
freestream velocity and speed of sound.

The wave equation is variable separable, with the acoustic pressure given by

$$
p(\xi, r, \theta, t) = \mathcal{P}(k_\mu r) e^{i(k_\xi \xi + k_\theta \theta + nN_{\text{Blades}} \Omega t)}
$$

where $\mathcal{P}$ is a linear combination of Bessel functions; $\omega = nN_{\text{Blades}} \Omega$ is the $n$'th harmonic of the rotor blade pass frequency; $k_\xi$, $k_\theta$, and $k_\phi$ are radial, axial and tangential wave numbers, respectively.

In an annular duct, the radial pressure variation is described by a linear combination of Bessel functions

$$
\mathcal{P}(k_\mu r) = J_{k_\xi}(k_\mu r) + Q_\mu Y_{k_\theta}(k_\mu r).
$$

The radial eigenvalues $k_\xi$ and $Q_\mu$ are determined to satisfy flow tangency conditions, zero radial velocity $u_r = 0$, at the inner and outer duct radii.

To determine the tangential wave number $k_\phi$, a $N_{\text{Blades}}$ bladed rotor and $N_{\text{vanes}}$ vaned stator in a duct are considered. The duct acoustic modes are generated by the unsteady pressures generated by the rotor blades rotating at speed $\Omega$ interacting with the downstream stationary stator vanes. The unsteady pressure pattern is the superposition of spinning modes which are generated at multiples of blade passage frequency $nN_{\text{Blades}} \Omega$. The number of lobes of the spinning pressure pattern, termed the spatial mode order, is a function of $N_{\text{Blades}}$ and $N_{\text{vanes}}$ [1].

The only modes generated by the rotor-stator interaction are specified by the tangential wave number values $k_\phi = nN_{\text{Blades}} + mN_{\text{vanes}}$ at $n$ times blade pass frequency. Note that while $k_\phi$ represents the spatial distribution of the pressure only integer values of $k_\phi$ are valid. The frequencies are the harmonics of blade passage frequency, i.e. $\omega = nN_{\text{Blades}} \Omega$, with the acoustic modes in the duct also responding at these frequencies. The phase speed $\Omega_\phi = nN_{\text{Blades}} \Omega/k_\phi$ is the
angular velocity of the \((k_{p,n})^{th}\) mode of the pressure pattern. Also, a negative value for \(k_0\) represents a backward traveling wave, i.e., the wave rotates in a direction opposite that of rotor rotation.

Although all of the acoustic pressure spatial modes of order \(k_0 = nN_{\text{blades}} + mN_{\text{vanes}}\) are generated by the rotor-stator interaction at the harmonics of blade passage frequency \(\omega = n N_{\text{blades}} \Omega\), only certain of these modes propagate to the far-field, with the rest decaying before reaching the far-field. Thus it is only those spatial modes that propagate to the far-field that represent the discrete-frequency noise received by an observer. The propagation of the acoustic pressure modes is specified by the axial dependence of the duct pressure waves, i.e., the axial wave number, specifically the expression under the radical of

\[
k_{\xi} = \frac{k_{\infty} M}{1 - M^2} \pm \sqrt{\left(\frac{k_{\infty} M}{1 - M^2}\right)^2 + \frac{k_{\infty}^2 - k_p^2}{1 - M^2}}
\]

* \(k_{\infty}^2 - k_p^2(1 - M^2) > 0\) - There are two real \(k_\xi\) values corresponding to two propagating pressure waves, one upstream and the other downstream.

* \(k_{\infty}^2 - k_p^2(1 - M^2) < 0\) - There are two complex \(k_\xi\) values corresponding to two decaying waves, one upstream and the other downstream.

* \(k_{\infty}^2 - k_p^2(1 - M^2) = 0\) - This is a resonance condition, with the resonant frequency known as the cut-off frequency because below the cut-off frequency the pressure waves decay in the axial direction or are "cut-off."

**Experimental Facility and Instrumentation**

The experiments are performed in the Purdue Rotating Annular Cascade, with a single stage turbomachine mounted in the test section, Figure 2. This facility is an open loop draw through type wind tunnel capable of test section velocities of 220 ft/sec (70 m/sec). Conditioned by a honeycomb section and an acoustically treated inlet plenum, the flow accelerates though a bellmouth inlet to the constant area annular test section. Exiting the test section, the flow is diffused into a large acoustically treated exit plenum. The flow is drawn through the facility by a centrifugal fan driven by a 300 hp (224 kW) electric motor located downstream of the exit plenum. The rotor speed is controlled using a 10 hp (7.5 kW) AC electric motor with variable speed drive, and the flow velocity is controlled using the inlet guide vanes of the centrifugal fan. Thus, the rotor speed and the flow velocity are independently controlled.

The annular test section is configured with a rotor comprised of 16 three inch wide perforated plates mounted normal to the rotor axis upstream of a stator row of NACA 65A012 uncambered airfoils with a 6.00 in. (15.24 cm) chord. The perforated plates, fabricated from 56% porosity aluminum sheet mounted on the rotor such that the plate width is normal to the rotor axis, generate large vortical gusts [2], thereby corresponding to forcing functions considered in mathematical models of rotor-stator interaction generated discrete tones [3,4]. For the passive rotor-dettuning experiments, 18 stators are utilized. For the active control experiments, the stator row is comprised of three vanes.

Acquisition and digitization of the microphone and shaft trigger signals is accomplished using three National Instruments NI-A2000 analog-to-digital boards installed in an Apple Macintosh Quadra 950 minicomputer. This system allows the simultaneous acquisition of twelve channels of data, initiated by the shaft trigger signal. Data are acquired over one rotor revolution, with random noise not linked to the rotor passage reduced by ensemble averaging.

The acoustic response is characterized as a summation of spatial modes generated at multiples of rotor blade pass frequency. Thus, the pressure measured by the microphone array is a function of both time and space. Discrete Fourier transforms are used to determine the measured pressure as a function of frequency and spatial mode [5]. The temporal transform is used to determine the microphone signals as a function of frequency. At a particular frequency, the spatial
transform determines the spatial modes which compose the acoustic response. When used in concert, the complex amplitude of the acoustic response can be determined for both forward and backward spinning spatial modes as a function of frequency.

The Fourier analysis of a continuous signal sampled at discrete locations has resolution limited by the number of microphones. A spatial mode higher than the Nyquist mode will be aliased into a mode below the Nyquist mode. A minimum of two samples of a sinusoidal signal is required to determine spatial mode order and signal amplitude. Applying the theory of Nyquist frequency to a spatial transform yields a critical spatial mode $k_{\text{critical}}$ which is related to the number of microphones $N$. The Nyquist critical spatial mode is given by $N/2$. For these experiments, with an array of 10 PCB 103A microphones, the Nyquist critical mode is 5 for the 10 microphone array all signals which have a spatial mode order above the Nyquist critical mode will be aliased below the Nyquist mode.

**RESULTS**

To investigate the fundamentals of both passive and active source control of discrete-frequency tones, a series of experiments are performed in the Purdue Rotating Annular Cascade Research Facility.

**Passive Source Control - Rotor Detuning**

This study considers a detuned rotor where the angular spacing is perturbed over two cycles.

$$\theta_{\text{detuned}} = \Delta \theta_{\text{tuned}} + r \sin \left( 4\pi \frac{r}{N_{\text{Blades}}} \right)$$

where $\Delta \theta_{\text{tuned}}$ is the tuned rotor tangential spacing, $\varepsilon$ is the detuning level and $r = 0, 1, 2, \ldots, N_{\text{Blades}} - 1$ is the blade index.

The excitation provided by a tuned rotor exists at multiples of blade pass frequency. The excitation provided by a detuned rotor also exists at multiples of blade pass frequency, but is also frequency modulated by the number of cycles in the perturbed detuned circumferential blade spacing. The detuned rotor will excite the stator at $(N_{\text{Blades}} \pm 21)$ times rotor pass frequency where $l$ is any arbitrary integer. Thus, a 16 bladed rotor detuned by a two cycle perturbation will excite the stator at $14$, $16$, $18$, $20$, $\cdots$ times the rotor shaft pass frequency. A detuned rotor can be considered, in the frequency domain, in the same manner as a tuned rotor where the number of rotor blades is replaced by the rotor shaft order of interest. This applies to the spatial modes generated by a rotor-stator interaction and the propagation/decay of the generated spatial mode.

The level of detuning for this study was chosen as 1/2, with the tuned and detuned rotor spacings depicted in Figure 3. The detuned rotor generates the following spatial modes: $k_0 = -2$ at 16xRPF (rotor pass frequency), $k_0 = 0$ at 18xRPF, and $k_0 = 2$ at 20xRPF. The $k_0 = -2$ spatial mode at 16xRPF is cut-on at 733 rpm, the $k_0 = 0$ spatial mode is cut-on for all frequencies, and the $k_0 = 2$ spatial mode is cut-on at 586 rotor shaft rpm.

The influence of rotor detuning should be considered over the entire spectrum. Thus, the overall intensity level is integrated for the tuned and detuned rotors as a function of rotor shaft rotation. The overall intensity level is reduced for rotor shaft rotation speeds over 740 rpm where the $k_0 = -2$ spatial mode is cut-on at blade pass frequency (16xRPF), Figure 4, as predicted.
The excitation provided by a tuned rotor exists at multiples of blade pass frequency. The excitation provided by a detuned rotor also exists at multiples of blade pass frequency, but is also frequency However, the intensity level of the stator response is increased by the detuned rotor for rotor shaft rotation speeds below 740 rpm where the $k_0 = -2$ spatial mode is cut-off, Figure 5.

**Active Source Control - Propagating Wave Control**

The active noise source control is accomplished with a speaker-dipole arrangement, Figure 6. Surrounding each stator are two compression drivers mounted to exponential horns. The control acoustic waves at blade pass frequency are enhanced with exponential horns designed for a cut-off frequency of 150 Hz, well below blade pass frequency (213 Hz). The horns open to the cascade endwall, with perforated plates having a transparency index of 20,176 covering the opening. Thus, sound with a frequency of 213 Hz has virtually no attenuation. The signal to the drivers is a sine wave with the same frequency as blade pass, with the drivers of each pair being 180° out of phase with one another. An optical sensor on the rotor produces a square wave trigger signal at blade pass frequency which serves as the input signal to the drivers and also provides the timing for the data acquisition. The phase at which the speakers are driven is defined as the gust-speaker phase.

A speaker-dipole system is used to cancel the propagating acoustic modes. The noise change is evaluated by dividing the measured sound pressure magnitude with the speaker-dipole by the noise measured with no speaker-dipole.

$$\Delta dB = 20 \log_{10} \left( \frac{p_{\text{controlled}}}{p_{\text{reference}}} \right)$$

With three stator vanes, the -2 and +1 spatial modes are generated by the rotor-stator interaction and propagate to the far-field. Figure 7 shows the influence of active control on the level of the propagating modes in the upstream duct. The acoustic response of the rotor-stator interaction is 106 and 92.3 dB for the -2 and +1 modes, respectively. Thus, the -2 mode is of primary importance. Sweeping the speaker power input, maximum mode control was found to occur with an input of 7.56 W rms to the speakers. The gust-speaker phase was optimized to reduce the -2 propagating mode from 106 dB to 88.9 dB, a 17.1 dB decrease. Changing the gust-speaker phase by 180°, Figure 7 also shows the influence of constructive interference with a nearly 6 dB increase in the level of -2 mode.

Figure 8 shows the influence of active control on the level of the propagating modes in the downstream duct. The acoustic response of the rotor-stator interaction is 105.8 and 89.8 dB for the -2 and +1 modes, respectively. Again, the -2 mode is of primary importance. With nearly the same levels measured in the downstream duct, maximum mode control was found with the same input of 7.56 W rms.
to the speakers. The gust-speaker phase was optimized to reduce the -2 propagating mode, in the downstream duct, from 105.8 dB to 90.7 dB, a 15.1 dB decrease. Changing the gust-speaker phase by 180°, Figure 8 shows the influence of constructive interference, with a 6 dB increase in the level of -2 mode.

Through all cases the -2 mode remained of primary importance, with the control having little effect on the -1 mode in either the upstream or downstream ducts. Thus, significant active noise control was realized in both the upstream and downstream ducts.

**Summary and Conclusions**

Advanced design high bypass turbomachines generate prominent discrete-frequency tones. These tones are generated by rotor-stator interactions, with certain specific acoustic modes generated. However, only certain of these modes propagate to the far-field, with these representing the far-field discrete-frequency noise. High bypass turbomachines also limit the effectiveness of current state-of-the-art acoustic treatments for suppression and source control. As prevailing noise regulations become ever more stringent, with reduction of turbomachine discrete-frequency tones a significant environmental concern, innovative control of turbomachine noise sources is increasingly important. Thus, this paper described a series of fundamental experiments to demonstrate passive and active source control of discrete-frequency noise.

Passive source control was accomplished by rotor detuning, defined as nonuniform rotor blade circumferential spacing. The modulated rotor blade spacing breaks up the fundamental periodicity of the rotor-stator interaction by affecting the frequency content of the excitation. This in turn affects the frequency content of the acoustic response. Thus, the influence of rotor detuning was determined from the overall intensity level as a function of rotor shaft rotation. The passive source control experiments were performed with 16 rotor blades and 18 stator vanes over a range of conditions, including both propagating and decaying response. Rotor detuning was demonstrated to consistently reduce the overall intensity level of the rotor-stator interaction when the \( k_e = -2 \) spatial mode was cut-on at blade pass frequency.

In the active source control technique, the acoustic propagating modes, i.e., the far field tone noise, were canceled by generating control propagating waves which interacted with those generated by the rotor-stator interaction. The origin of the acoustic response of the rotor-stator interaction is the stator vane unsteady surface pressures, theoretically modeled as dipole sources. Thus, the active discrete-frequency noise source control was accomplished utilizing a speaker-dipole arrangement around each stator. These produce control propagating acoustic waves which naturally mimic the rotor-stator interaction generated spatial modes, with the control parameter being the phase angle between the rotor wake and the speaker-dipole. These experiments were performed with 16 rotor blades and 3 stator vanes at a rotor shaft rotation of 800 rpm. This active noise source control system achieved 17.1 and 15.0 dB reductions of the primary interaction mode in the upstream and downstream ducts.

**References**